The Intriguing Story of Anomalous Resonance, Ghost Sources, and Superlenses

Graeme W. Milton
University of Utah

This will be an unusual lecture.

It is about scientific triumph

But also about bad scientific practices

It is a story that needs to be told

Graeme W. Milton
Durham, UK, 9am, Saturday July 16^{th}, 2016

A disturbing trend in science. Recognition and credit are going to the person who publicizes an idea most, not to the person who discovers the idea first.

On top of this, some respected scientists are not even referencing work that precedes theirs.

Others are following this, thinking that it is acceptable behavior.

One may win lots of
prizes/citations/promotions/accolades/press-releases,
even job offers,
this way, but it is not right.

There is good reason that the most credit should go to the person who discovers an idea first.*

Otherwise, some people might start to mine the literature, looking for papers with few citations, perhaps poorly written, but which contain wonderful ideas. They then may rewrite the ideas, draw publicity, and not even reference the original papers.

I do not believe this is the case with the respected scientists quoted on the previous page. Independent discoveries do frequently occur.

But a good scientist/mathematician should always refer to the original works, even when they precede his/hers. Otherwise, this casts doubts that they may indeed be a "**miner of other people's ideas**".

*People who propagate ideas should get some credit , as this is important to science, but this credit should not be at the expense of those who discovered the ideas first.

Main points that I want to draw attention to in the talk:*

(1) The superlens paper, Pendry's most cited paper, claims to have a perfect lens. **In fact the transmission is 0 not 1** when the source is close to the lens (our ignored 2007 paper). In other cases the image plane is in the "region of anomalous resonance" and this interferes with the image.

(2) It seems that in the case of four out of five of the most cited works of Sir John Pendry, that there are important papers preceding his which he rarely cites, **and continues to rarely cite**. That is not right in my view.

* This slide was inserted after the lecture

Taken from the website of META2016, where Sir John Pendry is giving a Plenary Talk *

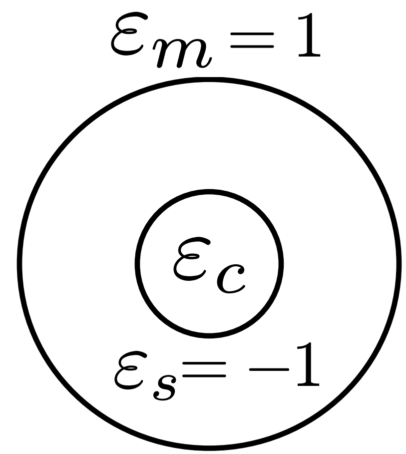
Plenary Lecture 6: Sir John Brian Pendry

Transformation optics, surface plasmons, and metasurfaces

His most famous work has introduced a new class of materials, metamaterials, whose electromagnetic properties depend on their internal structure rather than their chemical constitution. **He discovered that a perfect lens manufactured from negatively refracting material would circumvent Abbe's diffraction limit to spatial resolution, which has stood for more than a century.** His most recent **innovation of transformation optics** gives the metamaterial specifications required to rearrange electromagnetic field configurations at will, by representing the field distortions as a warping of the space in which they exist. In its simplest form the theory shows how we can direct field lines around a given obstacle and **thus provide a cloak of invisibility.** John Pendry's outstanding contributions have been awarded by many prizes, among which the Dirac Prize(1996), the Knight Bachelor (2004), the Royal Medal (2006), the Isaac Newton Medal (2013) and the Kavli Prize (2014).

* This slide was inserted after the lecture

PHYSICAL REVIEW B VOLUME 49, NUMBER 12 15 MARCH 1994-II

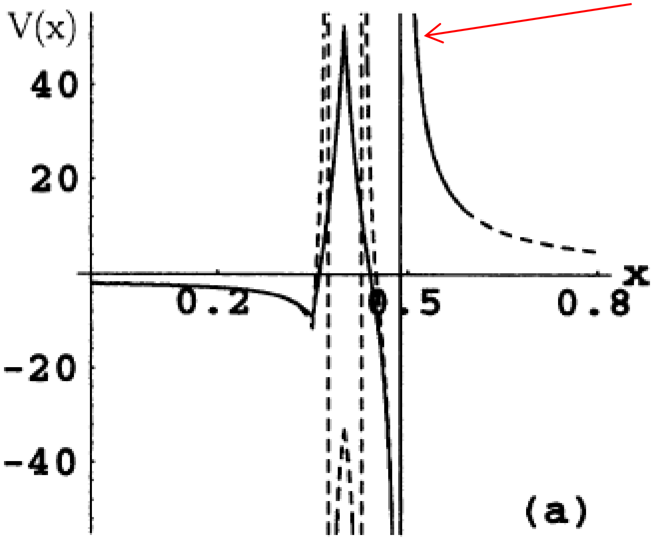


Optical and dielectric properties of partially resonant composites

N. A. Nicorovici and R. C. McPhedran
Department of Theoretical Physics, School of Physics, University of Sydney, Sydney, New South Wales 2006, Australia

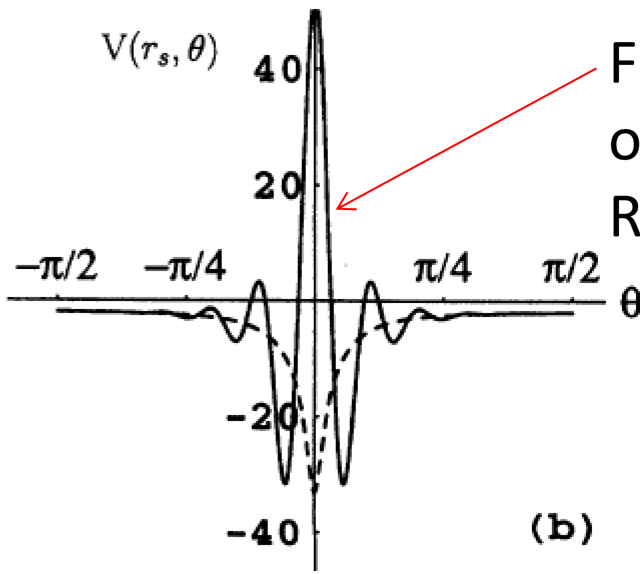
G. W. Milton*
Department of Mathematics, University of Utah, Salt Lake City, Utah 84112
(Received 2 November 1993)

First Discovery of a Ghost Source



(Shell radius=0.4, Core radius=0.35)

First Discovery of Anomalous Resonance



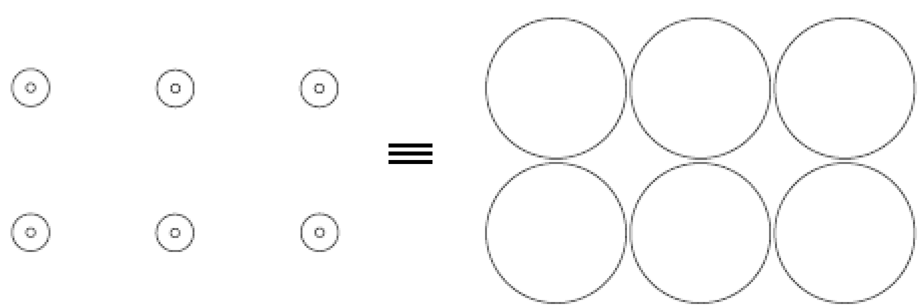
Ghost sources and anomalous resonance are the essential mechanisms that explain superlensing. I believe Sir John Pendry has referred to our paper only once (doi:10.1088/1367-2630/12/3/033047). Our work has been bought to his attention many times, since $\approx$ 2004

What was the history behind this landmark discovery?

Ross McPhedran and Nicolae Nicorovici were studying the effective dielectric constant ε_* of square arrays of coated disks, having a core of radius r_c, and dielectric constant ε_c, surrounded by a shell of outer radius r_s, and dielectric constant ε_s, embedded in a matrix having dielectric constant ε_m. Ross was doing the theory and Nicolae the numerics.

Ross discovered there were two surprising cases where the coefficients in the series expansion simplified drastically.

The first, particularly striking, case was when $\varepsilon_s = -\varepsilon_m$, in which case Ross found the shell acted to magnify the core by a factor of r_s^2/r_c^2, so it had the same effective dielectric constant as an array of disks of radius r_s^2/r_c, and dielectric constant ε_c



The second case was when $\varepsilon_s = -\varepsilon_c$ in which case the material had the same dielectric constant as an array of disks having radius r_s and dielectric constant ε_c. The results were published in 1993 in

Transport properties of a three-phase composite material: the square array of coated cylinders

BY N. A. NICOROVICI[1], R. C. MCPHEDRAN[1] AND G. W. MILTON[2]

I was a coauthor but honestly I can't remember what my contributions were*. Certainly the key discoveries in that paper were made by Ross.

We then decided to look at an isolated coated disk of radius r_c and dielectric constant ε_c surrounded by a shell having outer radius r_s and dielectric constant $\varepsilon_s = -\varepsilon_m$. We found that for any polynomial applied field, it responded exactly the same as a disk of dielectric constant ε_c and radius r_s^2/r_c.

*Ross reminded me that I was the one to come up with the representation of pole and zero trajectories on three hexagons, Figure 5 and Appendix C. Indeed I was quite proud of that. (Inserted after the lecture)

Then, still in 1993, I realized there was a ***paradox.***

If this equivalence held and if one had a dipole source sufficiently close to the equivalent disk of radius r_s^2/r_c and dielectric constant ε_c, then the field outside, by the method of images, should be that due to the actual source plus an image source. But in the original problem of the coated disk, that image source could sometimes **lie in the matrix**.

This violated everything we knew about image charges, and indeed the maximum principle since the potential should have its maximum in the matrix at the shell boundary or at infinity.

Clearly this demanded further investigation. I realized that to be physically and mathematically kosher one should add a small loss to the shell and take the limit as it tended to zero. I did the analysis and Nicolae the numerics**. This heralded the discovery of ghost charges and anomalous resonance, what turned out later to be the essential mechanisms for superresolution.**

All the results are in our 1994 paper (submitted in November 1993).

It is true that we could have drawn more attention to this discovery, especially by mentioning it in the abstract.

Honestly, there was so much completely new in that paper, and we were trying to condense it down to the page limits of Physical Review Letters, that some things were overlooked.

Unfortunately the referees did not share our views of the breakthrough nature of the paper and it only made it to the brief reports section of Physical Review B, to be forgotten by the community until about 2006.

I did realize its significance and sometime between 1993 and 1996 started a draft emphasizing the surprising nature of our findings.

That draft in its untouched original form is now on Researchgate

http://dx.doi.org/10.13140/RG.2.1.1477.5283 **TIMESTAMP: MAY 13th 1996**

Again, I emphasize that our findings **are published** in the 1994 paper.

How would you give a back of the envelope description of anomalous resonance?

Consider the analytic function

$$f(z) = \frac{1}{1-z}.$$

Consider the truncated series expansion

$$f_n(z) = \sum_{j=0}^{n} z^j.$$

Clearly as $n \to \infty$,

$$f_n(z) \to f(z), \quad \text{if } |z| < 1 \quad (\textbf{convergence})$$

We may then say there is a **ghost source** at $z = 1$.

If $|z| > 1$ then $f_n(z)$ develops more and more oscillations of higher and higher intensity and shorter "wavelength" as $n \to \infty$. (**anomalous resonance**).

Elementary! The difficulty is finding a physical system where $1/n$ is somehow correlated with the loss in the system, or with some parameter which goes to zero as the system "loses ellipticity". Also where the "region of anomalous resonance" is correlated with the position of the source.

Number of Citations does not establish validity

VOLUME 85, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 2000

Negative Refraction Makes a Perfect Lens

J. B. Pendry
Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
(Received 25 April 2000)

Almost 10,000 citations

John Pendry gave a talk in Edinburgh last month, referencing almost no one. At the end I asked him a question and it was clear that he did not understand how superlenses work, even in the lossless case, which is what this paper was about. **The truth is far stranger than Pendry envisaged**.

The true picture has been known since 2006, but ignored.

N.B. Another very significant paper, referred to by Pendry, was Veselago's 1968 paper showing one could get wave propagation in media with negative ε, μ.

Wrong explanations of how superlenses work abound in the literature.

Suppose the superlens is of thickness d **and the source is a distance $d_0 < d$ from the lens.**

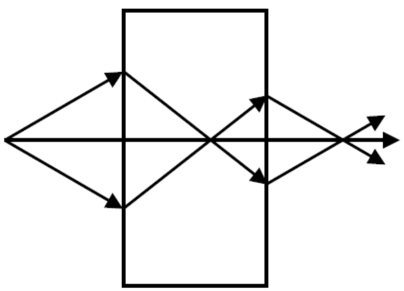
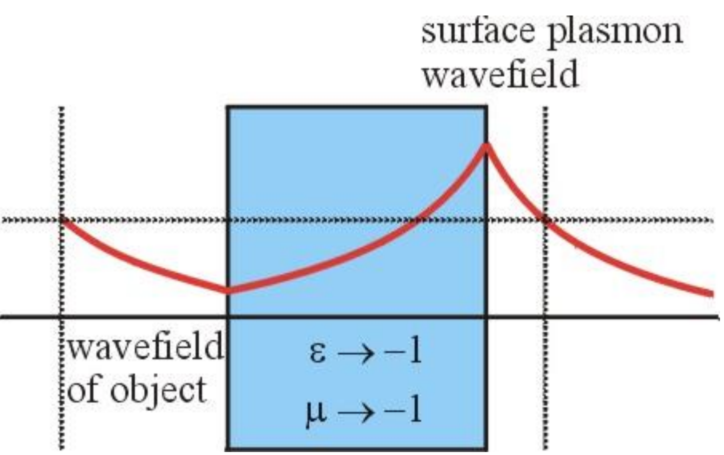


FIG. 1. A negative refractive index medium bends light to a negative angle with the surface normal. Light formerly diverging from a point source is set in reverse and converges back to a point. Released from the medium the light reaches a focus for a second time.

Pendry's original paper, also Veselago. Okay for negative refractive index but wrong for a superlens at any finite frequency.



Wrong, if $d_0 < d$

Pendry's website on July 10th 2016

Using Transformation Optics to map folded space to superlens

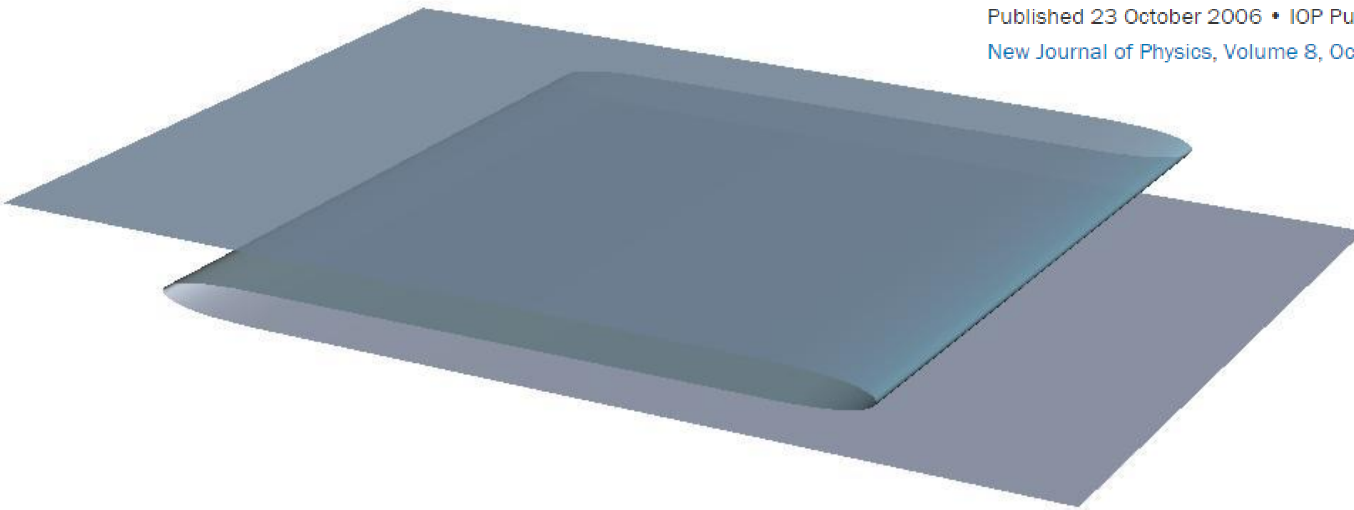
A beautiful idea:

New Journal of Physics
The open access journal at the forefront of physics

General relativity in electrical engineering

Ulf Leonhardt and Thomas G Philbin

Published 23 October 2006 • IOP Publishing and Deutsche Physikalische Gesellschaft
New Journal of Physics, Volume 8, October 2006



Pendry talks about this in his lectures but I have never heard him mention the above paper in this context.

"You can try out the secret of perfect imaging with a sheet of paper. Fold it as shown in the picture. Then cut a hole through the fold and open it. You get three identical copies of the hole. In optical imaging, the first hole represents the object you want to see, the other two holes are the images. One is formed where the fold went backwards; this is where the device does its magic, so the first image is formed inside the lens".

Incorrect,

Also incorrect is figure 3 in the above paper.

Ulf Leonhardt's webpage 10th July 2016 wrong if $d_0 < d$

Why are these wrong? An important paper:

122 J. Opt. Soc. Am. A/Vol. 21, No. 1/January 2004 D. Maystre and S. Enoch

Perfect lenses made with left-handed materials: Alice's mirror?

Daniel Maystre and Stefan Enoch

Institut Fresnel, Unité Mixte de Recherche 6133, Faculté des Sciences et Techniques de St. Jérôme (Case 161), 13397 Marseille Cedex 20, France

They noticed that each interface of the lens essentially acts as a mirror for electromagnetic fields.

The "reflections" of the true source also represent real sources that either produce energy , or are energy sinks. Without them , it is not a solution of Maxwell's equations.

123 Citations: Note as we are getting closer to the truth, the number of citations has decreased drastically.

One wonders: How many citations the paper that reveals the true story will have??????????

It is clear that the analysis in Pendry's initial paper is invalid for the case where the source is within a distance d of the lens, and this is the case that has attracted widest attention.

At best one could conjecture that a source would be perfectly imaged if it was within a distance d of the lens.

But in fact such a conjecture would be wrong half the time.

Another disturbing fact. My brilliant friend Alexei Efros (private communication, 2005) found that if you included loss in the lens, and let that loss approach zero, then there would be an infinite amount of power dissipated in the lens, if the source was closer than $d/2$ to the lens. At that time, he thought the lens violated energy conservation, and therefore that the concept of a perfect lens was flawed.

It was Efros's remark that led us to discover cloaking due to anomalous resonance in 2005 — published in 2006 before Pendry, Schurig and Smith, and Leonhardt.

We may (?) have been the first to introduce the word "cloaking" into the scientific literature, outside computer science.

Now we arrive at the true story of lossless superlenses

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Physica B 394 (2007) 171–175

PHYSICA B

www.elsevier.com/locate/physb

Opaque perfect lenses

Graeme W. Milton[a,*], Nicolae-Alexandru P. Nicorovici[b], Ross C. McPhedran[b]

21 Citations since 2007.

But one should exclude self citations and citations by students and postdocs.
This leaves 7 citations:

4 citations by mathematicians, 3 by non-mathematicians

One of these papers by non-mathematicians confirmed our analysis:

PHYSICAL REVIEW E **76**, 049903(E) (2007)

Erratum: Plane-wave solutions to frequency-domain and time-domain scattering from magnetodielectric slabs [Phys. Rev. E 73, 046608 (2006)]

Arthur D. Yaghjian and Thorkild B. Hansen
(Received 19 September 2007; published 30 October 2007)

The solution of Milton *et al.* [2] for an exponential time-domain line source produces similar divergent fields with increasing time about the front face (as well as the back face) of the slab, and we are indebted to Milton *et al.* for discovering these divergent front-face fields in the lossless time-domain solution.

It has been never been cited, although their original paper was cited 13 times.

It’s a story that’s happened before. Recall the paper:

Optical and dielectric properties of partially resonant composites

Authors NA Nicorovici, RC McPhedran, Graeme W Milton

Publication date 1994/3/15

Journal Physical Review B

Volume 49

Issue 12

Pages 8479

Publisher American Physical Society

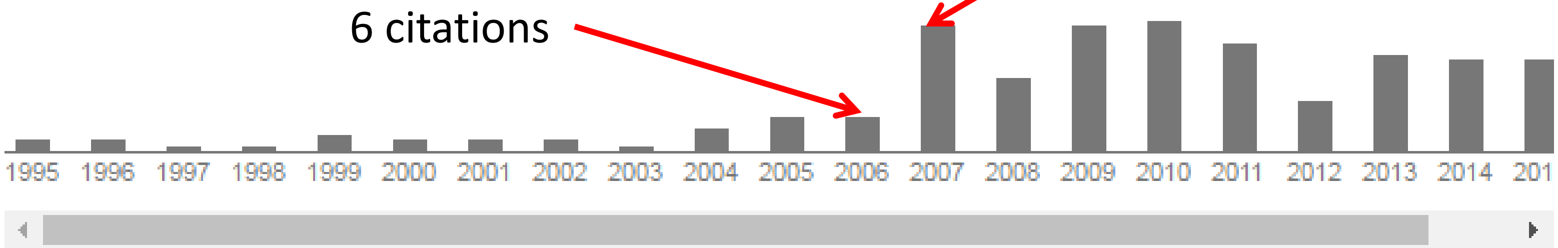
First discovery of ghost sources and anomalous resonance. From 1994 to 2006, it had essentially only been self-referenced by us.

Description Abstract We analyze the two-dimensional potential around a coated cylinder placed in a nonuniform field. In two special cases the system behaves as if the core of the cylinder were enlarged and the shell absent. These are when the shell dielectric constant is the negative of either the core dielectric constant or the matrix dielectric constant. When the shell dielectric constant has a small imaginary part, the field can exhibit large fluctuations which remain localized near the surface of the coated cylinder.

Total citations Cited by 199

22 citations

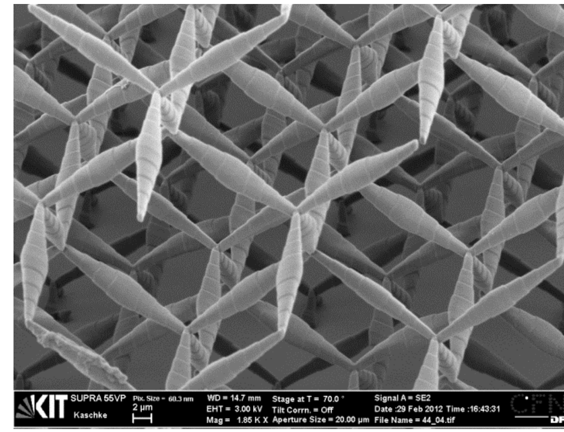
6 citations



ANOTHER EXAMPLE: The story of pentamode materials: web search pentamode

"In addition, the "holy grail" of mechanical materials, namely pentamode materials [4] that can be seen as the mother of all materials, might become accessible as well. Pentamodes, suggested by Milton and Cherkaev in 1995, [27] are solids that behave like fluids with a very small effective shear modulus."

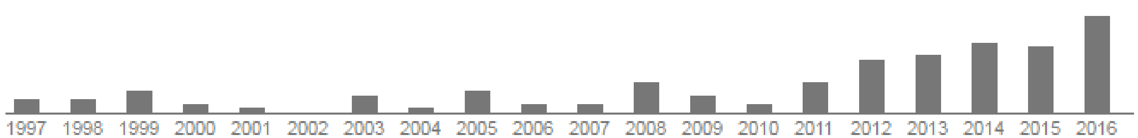
Wegeners Group, 2012 DOI: 10.1002/adma.201200584



Realized by them in 2012: DOI: 10.1063/1.4709436

Which elasticity tensors are realizable?

Authors	Graeme W Milton, Andrej V Cherkaev
Publication date	1995/10/1
Journal	Journal of engineering materials and technology
Volume	117
Issue	4
Pages	483-493
Publisher	American Society of Mechanical Engineers
Description	Abstract It is shown that any given positive definite fourth order tensor satisfying the usual symmetries of elasticity tensors can be realized as the effective elasticity tensor of a two-phase composite comprised of a sufficiently compliant isotropic phase and a sufficiently rigid isotropic phase configured in an suitable microstructure. The building blocks for constructing this composite are what we call extremal materials. These are composites of the two phases which are extremely stiff to a set of arbitrary given stresses and, at the same time, are ...
Total citations	Cited by 126



Only appreciated after 2010

I take the view, maybe naïve, that good work will ultimately be recognized.

So will you please explain how loss-less superlenses work ?

(1) As there exists no time-harmonic solution, one has to turn on the source exponentially slowly, with amplitude

$$E(t) = E_0(t_0)e^{-i\omega_0 t}e^{t/t_0} = E_0(t_0)e^{-i\omega t}, \quad \omega = \omega_0 + i/t_0$$

(2) Rather than increasing t we fix t and let t_0 increase:

t_0 measures how long the source has been "on "

(3) Due to dispersion, $\varepsilon(\omega)$ and $\mu(\omega)$ in the lens cannot equal -1 at nearby frequencies. In the lens one has:

$$\varepsilon(\omega) = -1 + a_\varepsilon(\omega - \omega_0) + \mathcal{O}(\omega - \omega_0)^2 = -1 + ia_\varepsilon/t_0 + \mathcal{O}(1/t_0^2)$$
$$\mu(\omega) = -1 + a_\mu(\omega - \omega_0) + \mathcal{O}(\omega - \omega_0)^2 = -1 + ia_\mu/t_0 + \mathcal{O}(1/t_0^2)$$

(4) Due to causality and passivity,

$$a_\varepsilon = \frac{d\varepsilon(\omega)}{d\omega}\Big|_{\omega=\omega_0} \geq \frac{4}{\omega_0} \qquad a_\mu = \frac{d\mu(\omega)}{d\omega}\Big|_{\omega=\omega_0} \geq \frac{4}{\omega_0}$$

(5) So when frequency ω has very tiny imaginary part the material in the lens has constants ε, μ having very tiny imaginary parts.

The response of lenses with having a tiny imaginary part of their moduli had been studied before.

Another point: if you turn on a source a distance d_0 from the lens with amplitude E_0 at time $t = 0$

From A. D. Yaghjian, T. B. Hansen, Plane-wave solutions to frequency-domain and time-domain scattering from magnetodielectric slabs (2006) one sees that:

The time derivative of the stored electrical energy is $\frac{dS_E}{dt} \sim E_0^2 t^{1-2d_0/d}$, which increases (sublinearly) with time if $d_0 < d/2$

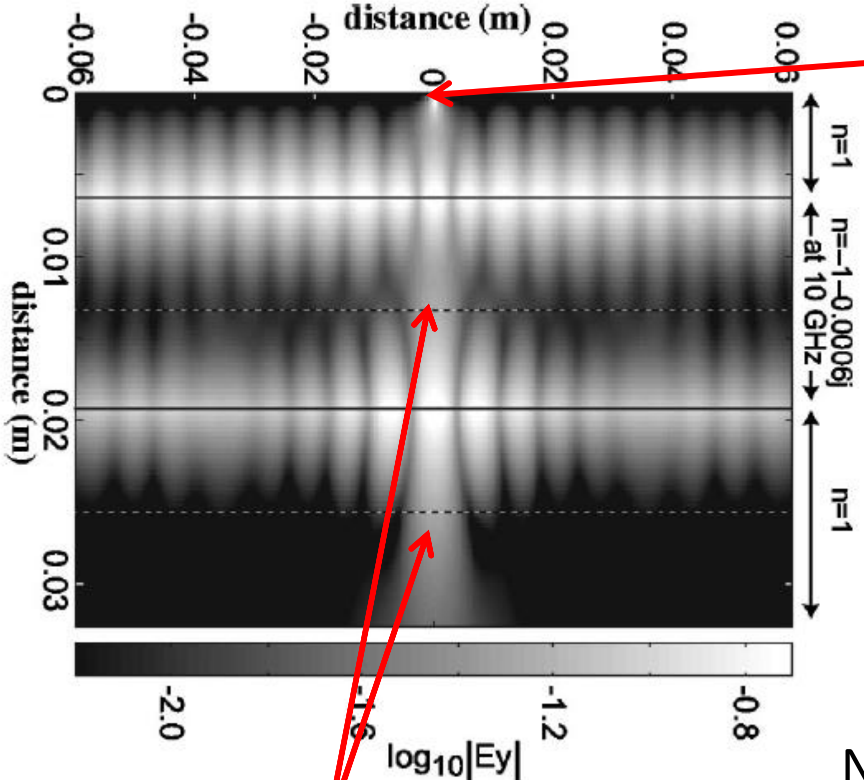
So the amplitude E_0 cannot remain independent of time, but rather must go to zero as $t \to \infty$

Numerical calculations with constant E_0 are unphysical because the source ultimately ends up consuming more energy per unit time, than produced by say an entire power plant (how long this takes, which may be exceedingly long, depends on the choice of E_0) .

To look at what happens as t increases with a source producing constant power, we need only study what happens when there is a tiny loss in the lens.

Work by Garcia and Nieto-Vesperinas (2002) and Pokrovsky and Efros (2002) indicated large fields between ghost sources.

(Anomalous resonance and ghost sources had been rediscovered)



Actual Source

Anomalously resonant region

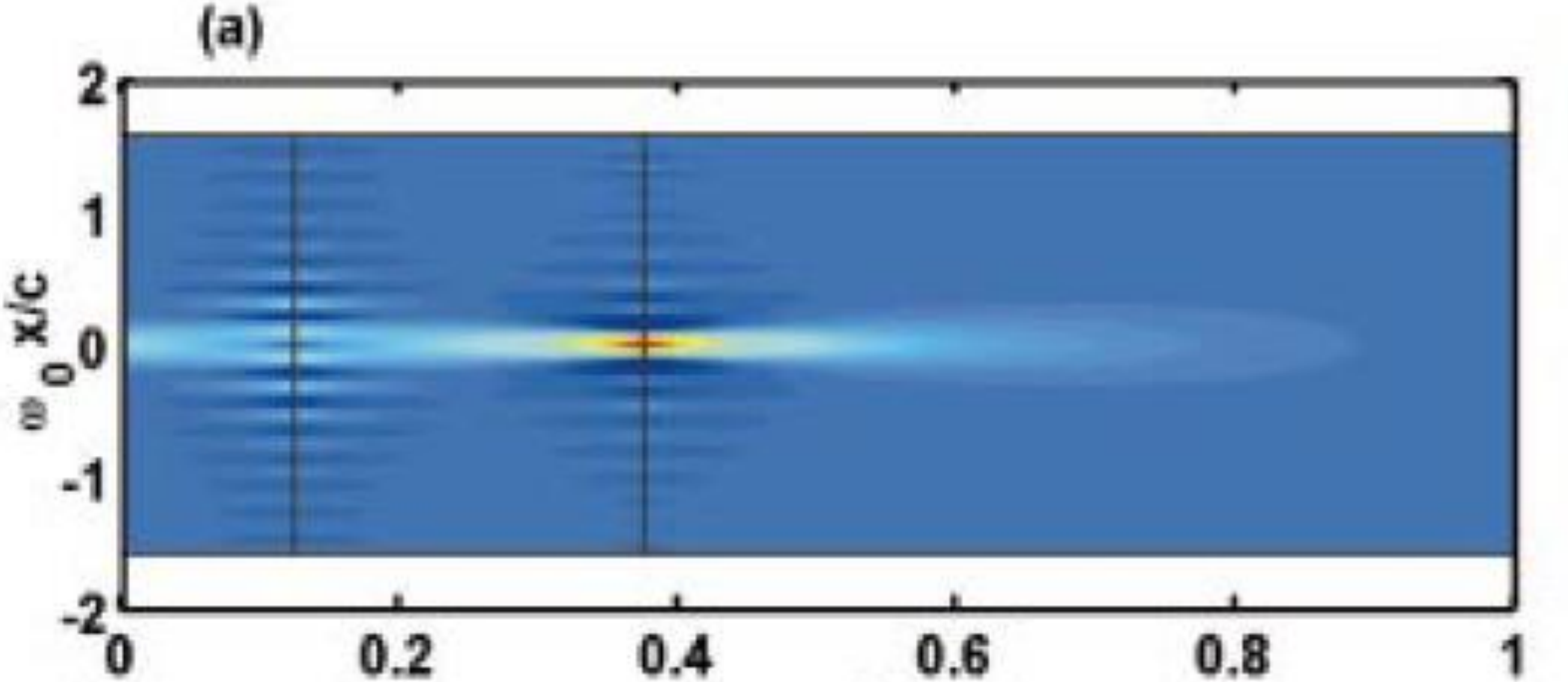
Anomalously resonant region

More than just surface plasmons

Ghost Sources

Note it is the wavelength in the regions of anomalous resonance that sets the scale of resolution. Lousy resolution if any significant loss.

Numerical Results of Cummer (2003)



Numerical results of Shvets (2003) also indicating the anomalously resonant regions centered at both the front and back sides of the lens.

These simulations are for constant amplitude: for constant power, they must be like those in our first paper on cloaking due to anomalous resonance (2005)

PROCEEDINGS OF THE ROYAL SOCIETY A

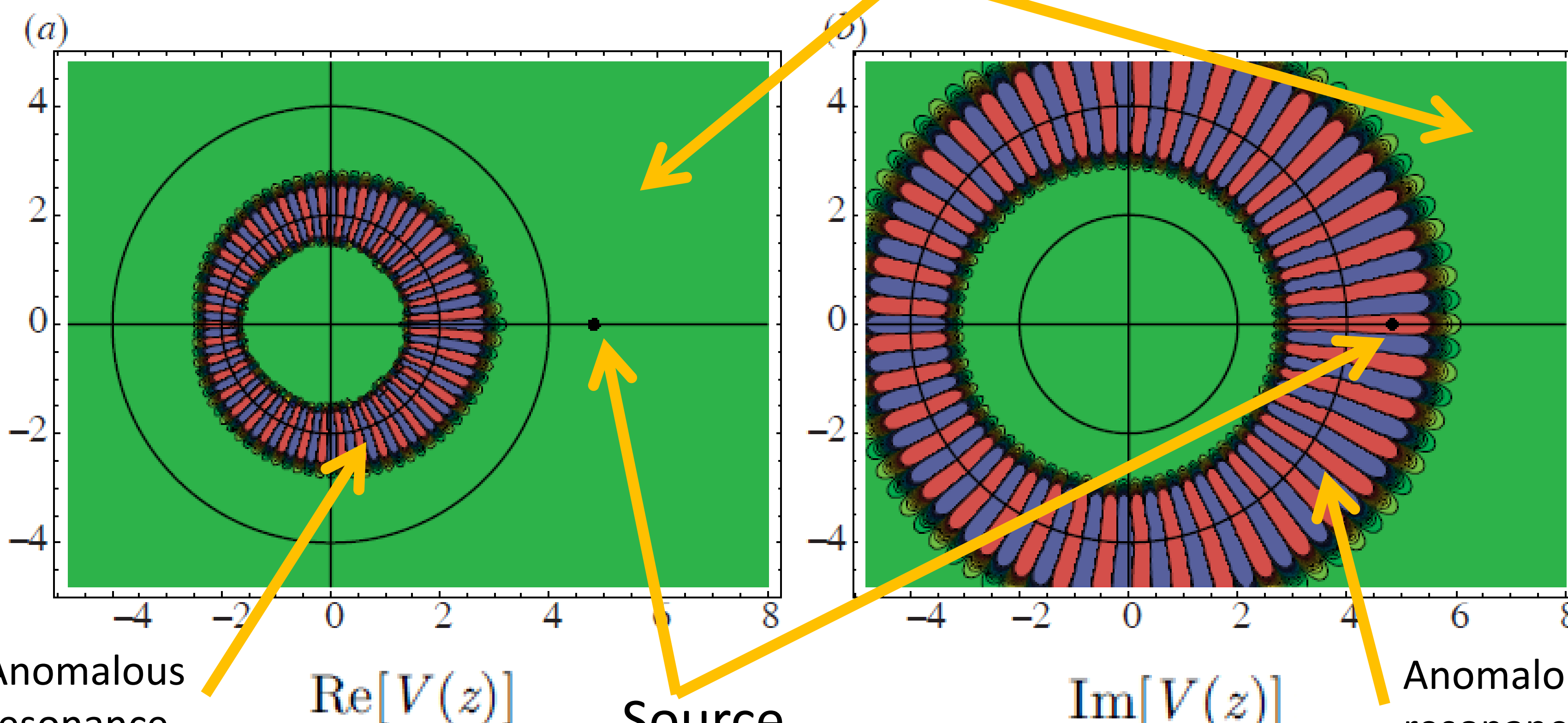
Proc. R. Soc. A (2006) **462**, 3027–3059
doi:10.1098/rspa.2006.1715
Published online 3 May 2006

On the cloaking effects associated with anomalous localized resonance

By Graeme W. Milton[1,*] and Nicolae-Alexandru P. Nicorovici[2]

Quasistatic equations. Constant power source, not constant amplitude source, in Figure 4 with localized fields:

Note, almost no fields outside the resonant region:



Anomalous resonance

Source

Anomalous resonance

So, with a dipolar point source, at long times essentially all the energy gets funnelled into the anomalously resonant regions.

The energy there builds up almost linear with time at these long times

The transmission goes to zero (contrary to Pendry's claim that it should go to 1)

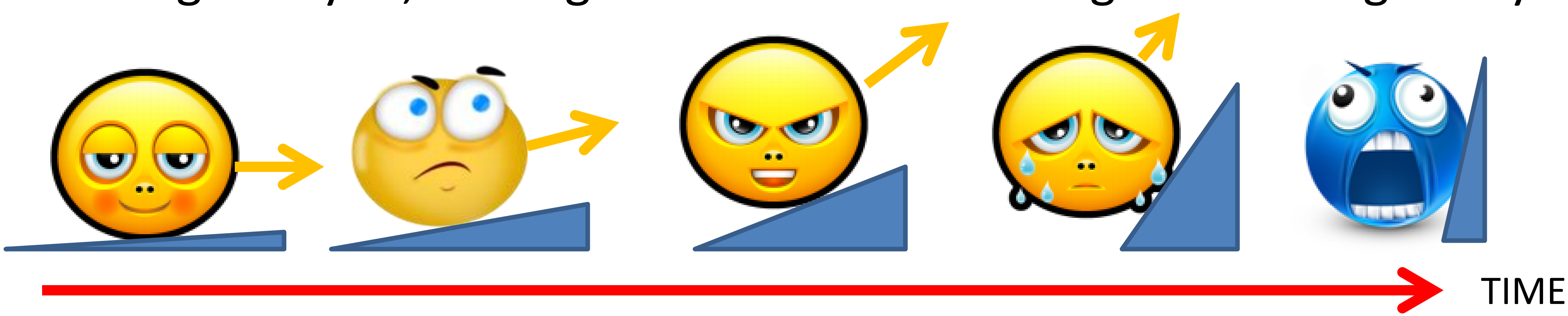
More remarkably, no energy gets propagated in the direction away from the lens either. In some sense, at long times there is no radiation emitted from the source in the direction away from the lens.

The source becomes cloaked in the long time limit.

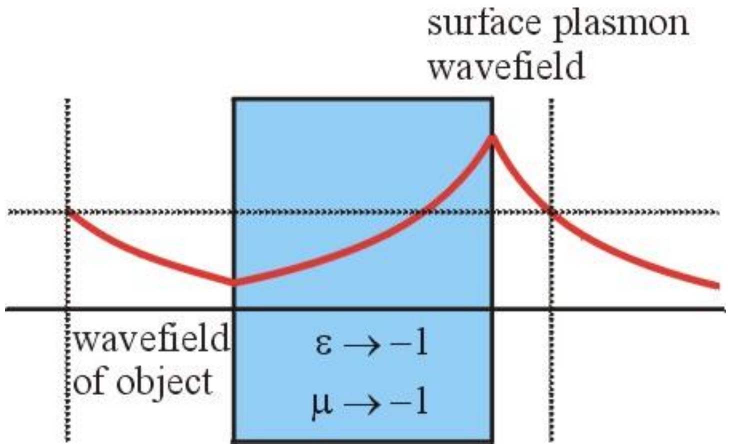
How I see it physically (roughly speaking).

Suppose the source is a negative charge oscillating along a line perpendicular to the lens around a fixed positive charge with constant power being supplied. This source is switched on at time $t = 0$.

The region of anomalous resonance develops and interacts with the source. It is such that the negative charge feels an electric field force which is always against its direction of motion. It is like the charge is "running uphill all the time". Its like going for a bike ride with the wind against you, turning around and still finding the wind against you.



It has to battle this, and as time goes on the power supply is drained so much that the negative charge can hardly move. All the energy is being pumped into the region of anomalous resonance.



Wrong, If $d_0 < d$ Pendry's website on July 10th 2016

APPLIED PHYSICS LETTERS **87**, 231113 (2005)

Optimizing the superlens: Manipulating geometry to enhance the resolution

Viktor A. Podolskiy[a] and Nicholas A. Kuhta

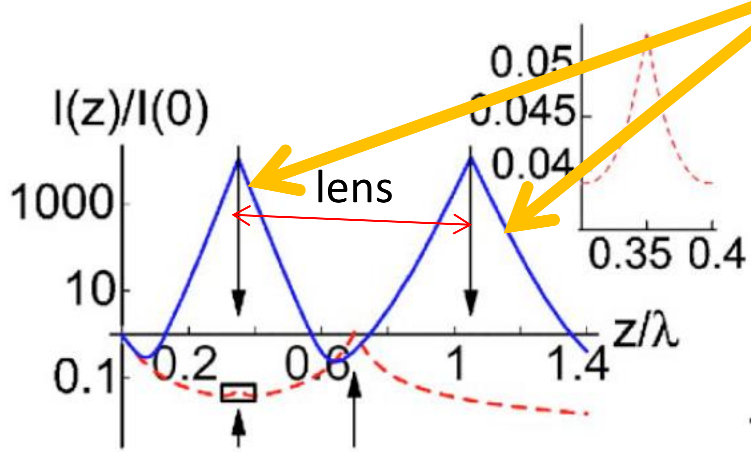
Physics Department, 301 Weniger Hall, Oregon State University, Corvallis, Oregon 97331

Graeme W. Milton

Department of Mathematics, University of Utah, Salt Lake City, Utah 84112

Field intensity exponentially high at both interfaces

Note Logarithmic Scale



Correct, 2005

57 citations,

others papers too

What about if the source is a distance between $d/2$ and d from the lens?

Then the source is **not cloaked** [Rigorous proof: Hoai-Minh Nguyen, Annales de l'Institut Henri Poincare – Nonlinear Analysis, 32 (2015), 471-484] but as mentioned in our 2005 paper, **there is another very significant problem**:

Then the image plane lies in the region of anomalous resonance, within a distance $d/2$ of the lens.

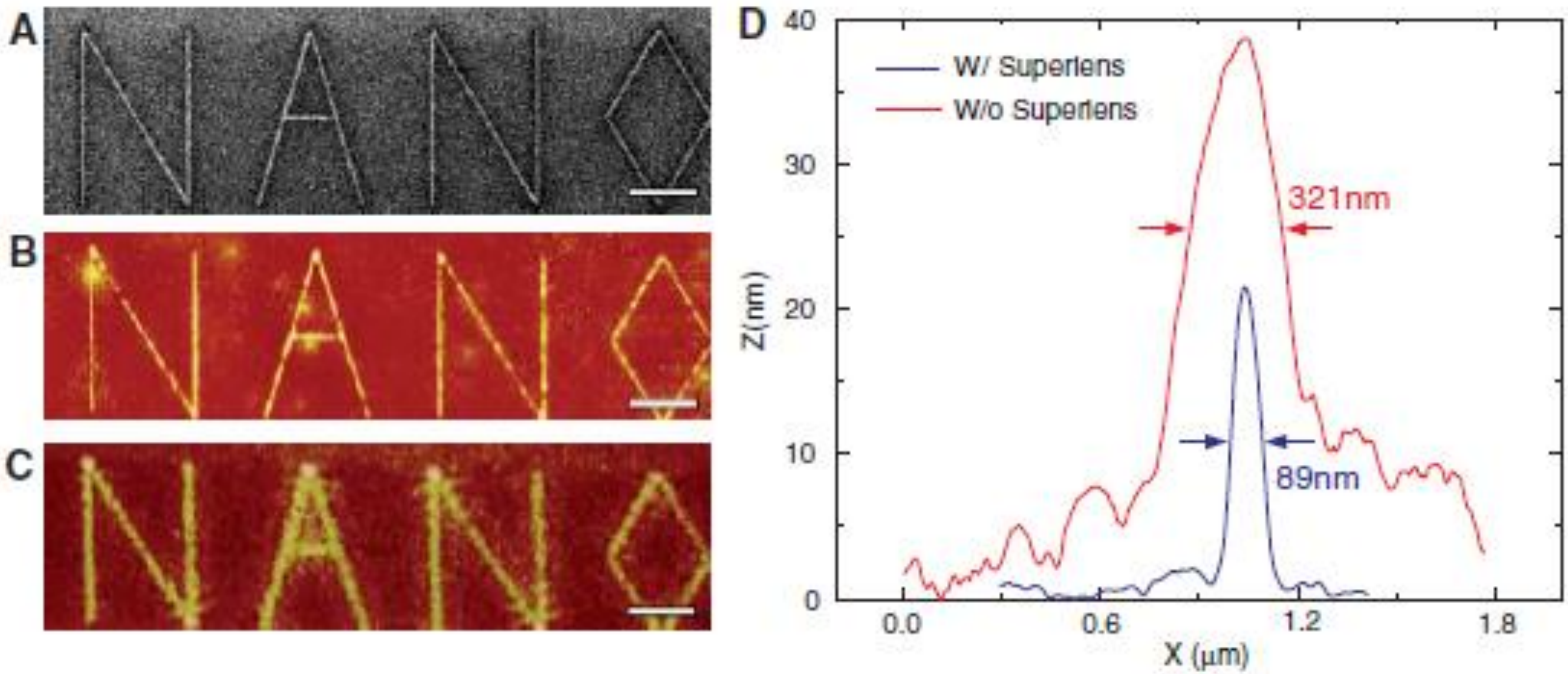
So if we put something at the image plane, it should surely interfere with the anomalous resonance and affect the image. Also whatever is detecting the image will also likely be susceptible to the fields of anomalous resonance.

More analysis needs to be done to clarify what happens.

Perhaps the lens is only good for imaging when the source is exactly $d/2$ from the lens, but even then I am not sure. Again more careful analysis needs to be done.

What about experiments?

Fang, Lee, Sun, Zhang (2005)



Very beautiful, and careful experiments, but I would be more convinced if the image were more complicated than a line, for example, if the spacing between letters was less than the wavelength.

How close was our 1993 –1994 work to Pendry's 2000 paper?

A slab is a limiting case of a cylindrical shell with large radius.

Our work was for quasistatics while Pendry's work was for the wave equation.

Interestingly , the anomalously resonant field in front
of the lens that causes the cloaking is frequency independent:

On the cloaking effects associated with anomalous localized resonance (Milton and Nicorovici, 2006)

In particular, in the resonant region in front of the lens, we have

$$\left.\begin{aligned} E_x^r(x,y) &= -[g_{\mathrm{m}}^{\mathrm{e}\prime}(z) + g_{\mathrm{m}}^{\mathrm{e}\prime}(\bar{z})]/2 - [g_{\mathrm{m}}^{\mathrm{o}\prime}(z) - g_{\mathrm{m}}^{\mathrm{o}\prime}(\bar{z})]/(2\mathrm{i}), \\ E_y^r(x,y) &= -\mathrm{i}[g_{\mathrm{m}}^{\mathrm{e}\prime}(z) - g_{\mathrm{m}}^{\mathrm{e}\prime}(\bar{z})]/2 - [g_{\mathrm{m}}^{\mathrm{o}\prime}(z) + g_{\mathrm{m}}^{\mathrm{o}\prime}(\bar{z})]/2, \end{aligned}\right\} \tag{4.25}$$

where

$$\begin{aligned} g_{\mathrm{m}}^{\mathrm{p}\prime}(z) = \mathrm{d}g_{\mathrm{m}}^{\mathrm{p}}(z)/\mathrm{d}z &= \mathrm{i}qk^{\mathrm{p}}[(1/d)\log(\epsilon/2)](\epsilon/2)^{(2d_0-d-z)/d} Q_0(2d-2d_0+z) \\ &\quad - \mathrm{i}qk^{\mathrm{p}}(\epsilon/2)^{(2d_0-d-z)/d} Q_0'(2d-2d_0+z) \\ &\approx \mathrm{i}qk^{\mathrm{p}}[(1/d)\log(\epsilon/2)](\epsilon/2)^{(2d_0-d-z)/d} Q_0(2d-2d_0+z), \end{aligned} \tag{4.26}$$

Independent of ω

It is the same as the quasistatic field

The quasistatic approximation for it is valid, not because the frequency is low, but rather because the field gradients are so large.

How I think about it:

In Maxwell's equations at constant frequency ω ,

$$\nabla \times \mathbf{E} = i\omega\mathbf{B}$$

$$\nabla \times \mathbf{B} = -i\omega\mathbf{D}$$

the rough idea is that the left hand side dominates the right if the characteristic length associated with $1/\omega$ (the wavelength) is much larger than the structure.

Or if the gradients on the left are enormous. Then we have the quasistatic equations

$$\nabla \times \mathbf{E} = 0, \quad \nabla \times \mathbf{B} = 0$$

Quasistatic cloaking of two-dimensional polarizable discrete systems by anomalous resonance

Nicolae-Alexandru P. Nicorovici, Graeme W. Milton, Ross C. McPhedran, and Lindsay C. Botten

Author Affiliations

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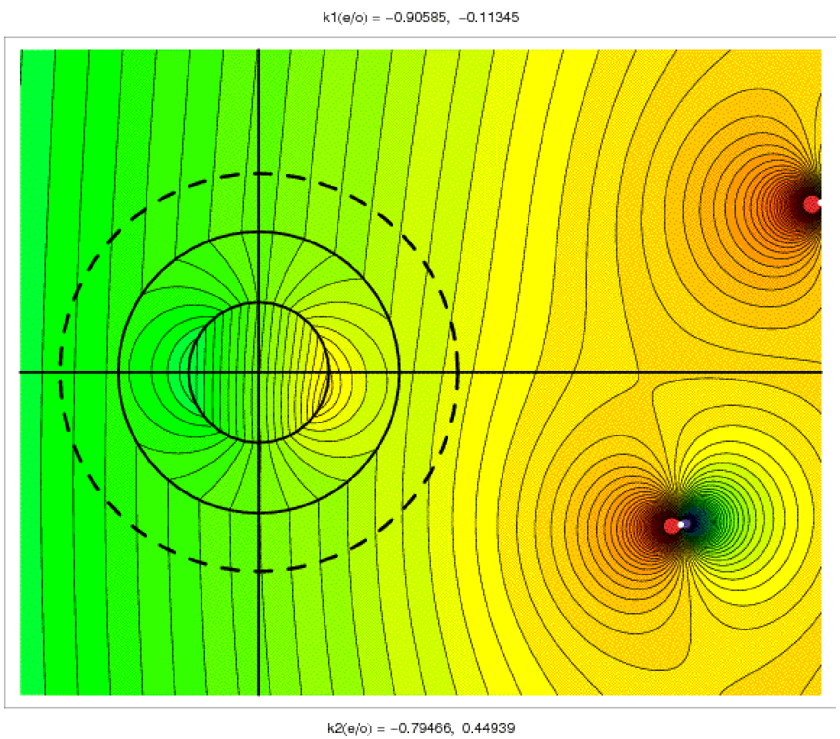
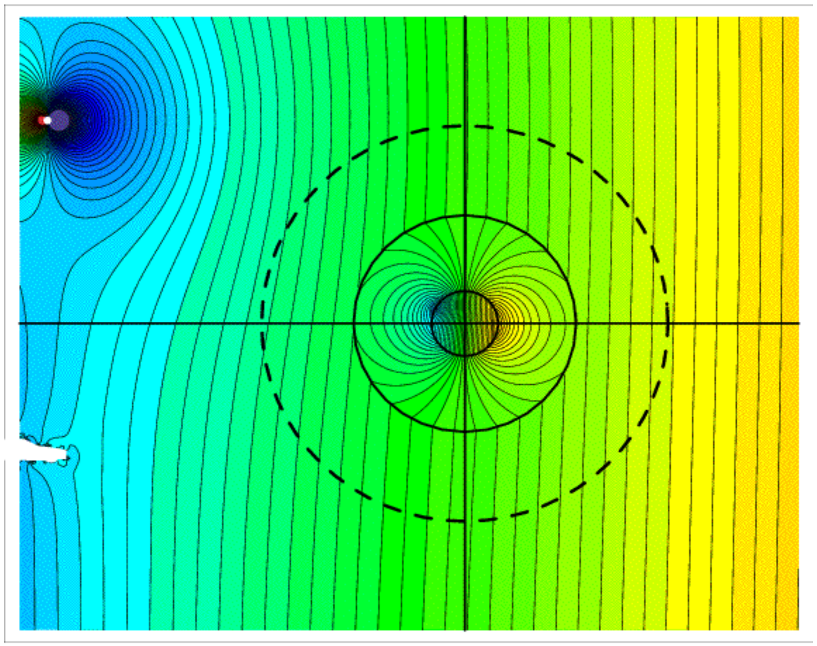




What happens in the time domain?

4594 OPTICS LETTERS / Vol. 37, No. 22 / November 15, 2012

On the time evolution of the cloaking effect of a metamaterial slab

Meng Xiao,[1] Xueqin Huang,[1] Jian-Wen Dong,[1,2] and C. T. Chan[1,*]

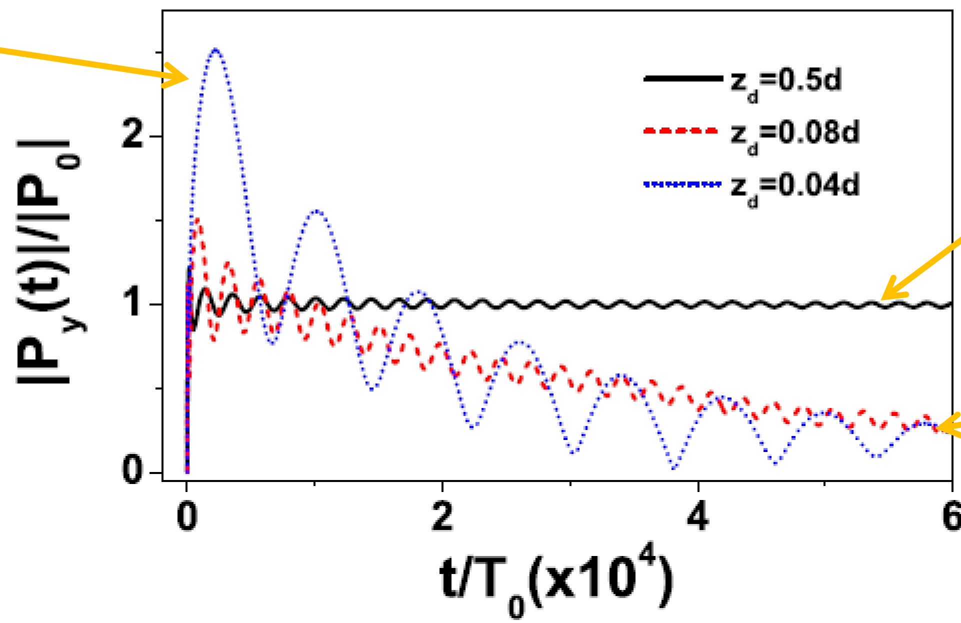


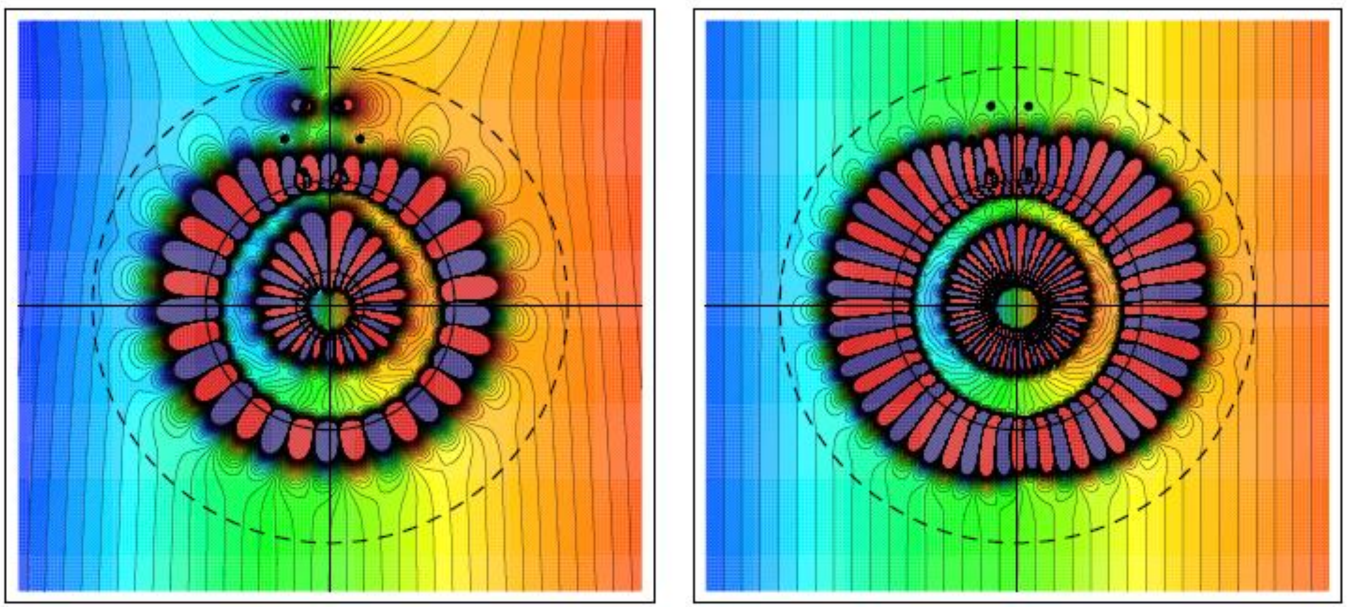
Fig. 2. (Color online) Time evolution of the normalized induced dipole moment of the particle $|P_y(t)|/|\boldsymbol{P}_0|$ for different values of z_d (distance between the particle and the slab) for $\delta = 10^{-6}$, $t_s = 1$.

New Journal of Physics
The open access journal at the forefront of physics

Solutions in folded geometries, and associated cloaking due to anomalous resonance

Graeme W Milton[1], Nicolae-Alexandru P Nicorovici[2], Ross C McPhedran[2], Kirill Cherednichenko[3] and Zubin Jacob[4]

Published 27 November 2008 • IOP Publishing and Deutsche Physikalische Gesellschaft
New Journal of Physics, Volume 10, November 2008
Focus on Cloaking and Transformation Optics



$$\varepsilon_s = -1 + 10^{-9} i \qquad \varepsilon_s = -1 + 10^{-15} i.$$

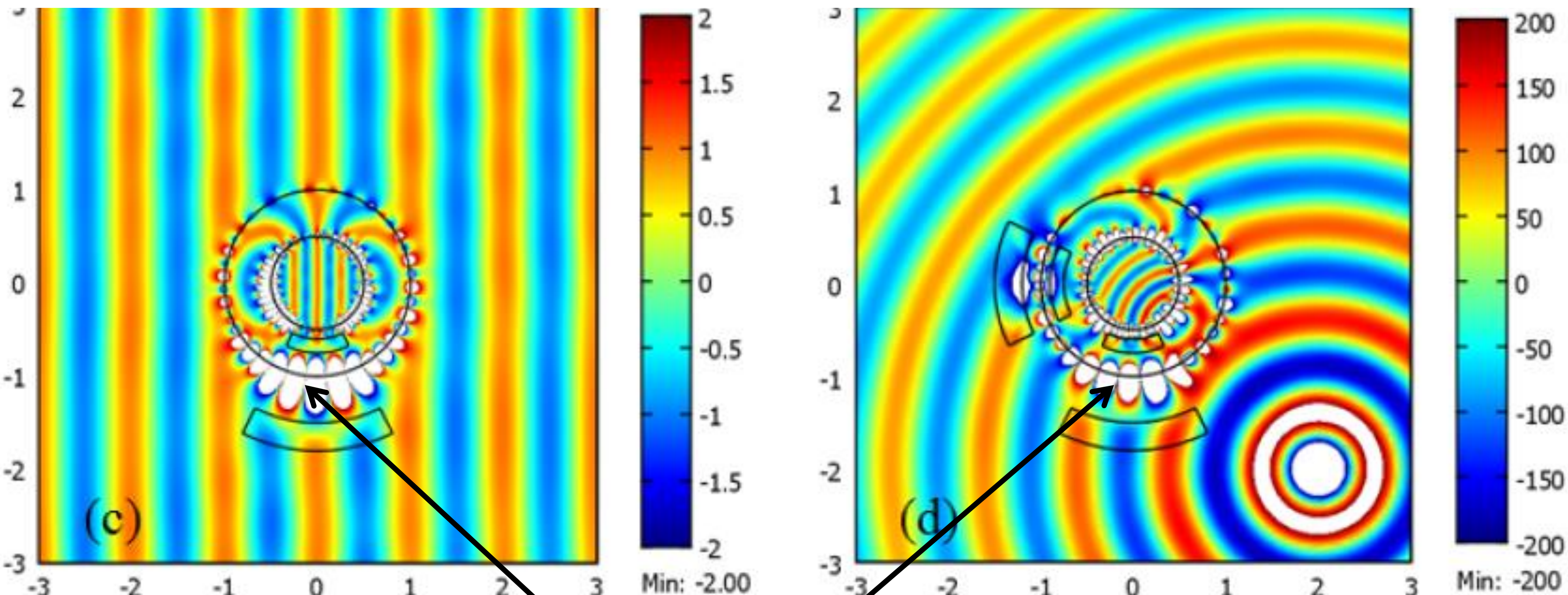
Note: folding idea different to that of Leonhardt and Philbin (2006) [DOI: 10.1088/1367-2630/8/10/247](https://doi.org/10.1088/1367-2630/8/10/247) in that one has different fields on the "three different sheets"

Another Appearance of Anomalous Resonance:

Selected for a Viewpoint in *Physics*
PRL **102,** 093901 (2009) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2009

Complementary Media Invisibility Cloak that Cloaks Objects at a Distance Outside the Cloaking Shell

Yun Lai, Huanyang Chen, Zhao-Qing Zhang, and C. T. Chan



Anomalous resonance

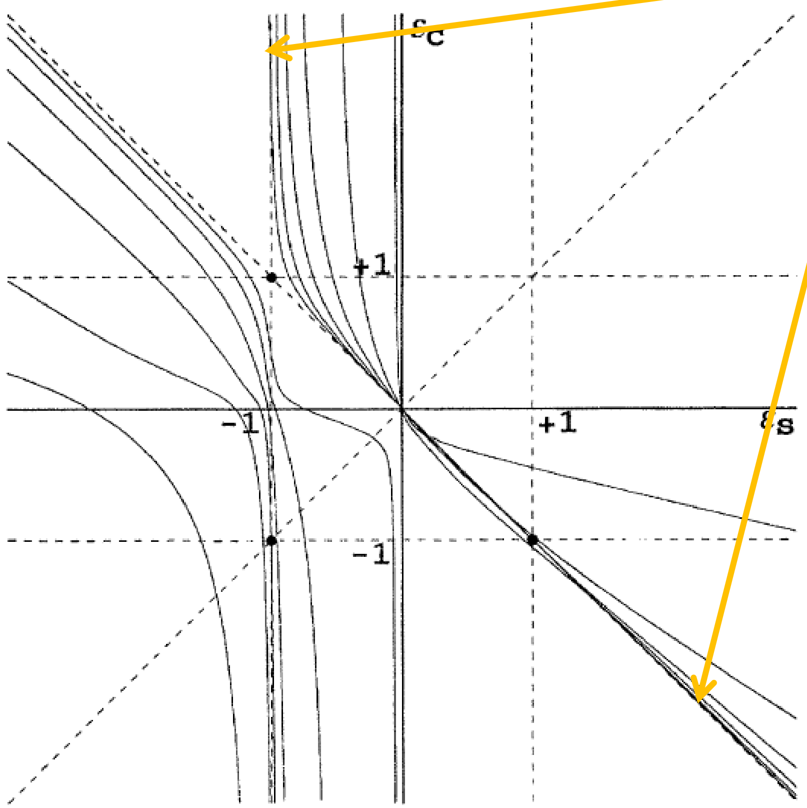
Proved by Nguyen and Nguyen, Cloaking using complementary media for the Helmholtz equation and a three spheres inequality for second order elliptic equations (2015)

While normal resonances are associated with poles,
anomalous resonance seems to be associated with essential singularities

From our 1993 paper:

5. Essential singularities, pole and zero trajectories

Figure 8



Lines of Anomalous Resonance, also essential singularity lines of the effective dielectric constant as a function of the component dielectric constants.

Also see:

Spectral theory of a Neumann —Poincare-type operator and analysis of cloaking due to anomalous localized resonance
(with H.Ammari, G.Ciraolo, H.Kang, and H.Lee),
Arch. Rat. Mech. Anal. 208, 667-692 (2013)

While the original proofs of cloaking due to anomalous resonance were for a finite number of dipole sources in $2d$ quasistatics, or for a single dipole source in $3d$ quasistatics, or for a single dipole source at any frequency,

The cloaking extends to small particles, small compared with the wavelength of the anomalous resonance

Bouchitte and Schweizer, 2010

The cloaking extends to sources of finite size.

Ammari, Ciraolo, Kang, Lee, and Milton, 2013, 2014
Kohn, Lu, Schweizer, and Weinstein, 2014
Nguyen, 2015
Meklachi, Milton, Onofrei, Thaler, and Funchess, 2016

The cloaking extends to objects of finite fixed size.
A major result: Hoai-Minh Nguyen (submitted, 2016)

Sometimes the cloaking is only partial

Bruno and Lintner, 2007

Or sometimes the cloaking is non-existent

Milton and Nicorovici, 2006
Ammari, Ciraolo, Kang, Lee, and Milton, 2013
Kohn, Lu, Schweizer, and Weinstein, 2014
Onofrei and Thaler, 2016

The cloaking extends to passive objects or active sources at finite wavelength

Nicorovici, McPhedran, Enoch, and Tayeb 2008
Kettunen, Lassas, and Ola, 2014
Nguyen, 2015, 2016 (submitted)
Onofrei and Thaler, 2016

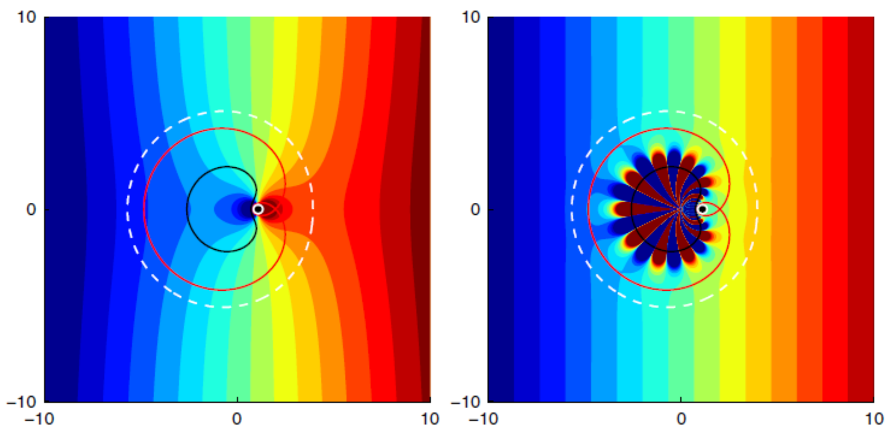
To magnetoelectric and thermoelectric systems

Milton, Nicorovici, McPhedran, and Podolskiy, 2005

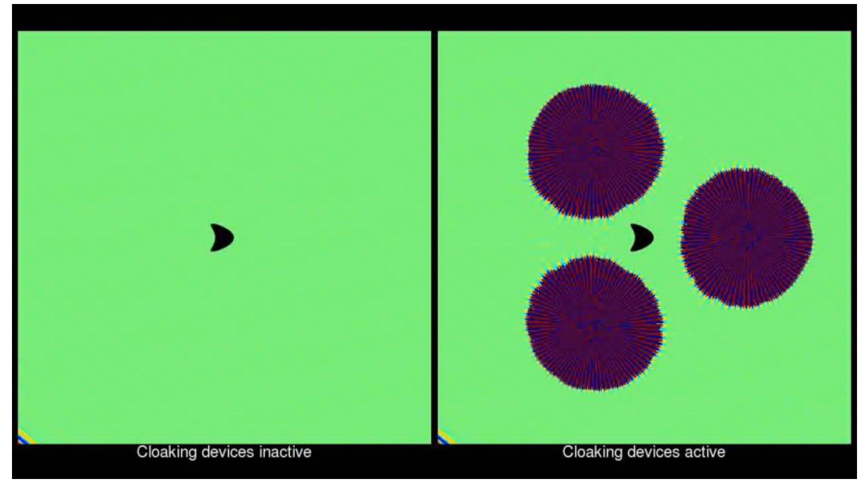
and to the elasticity equations

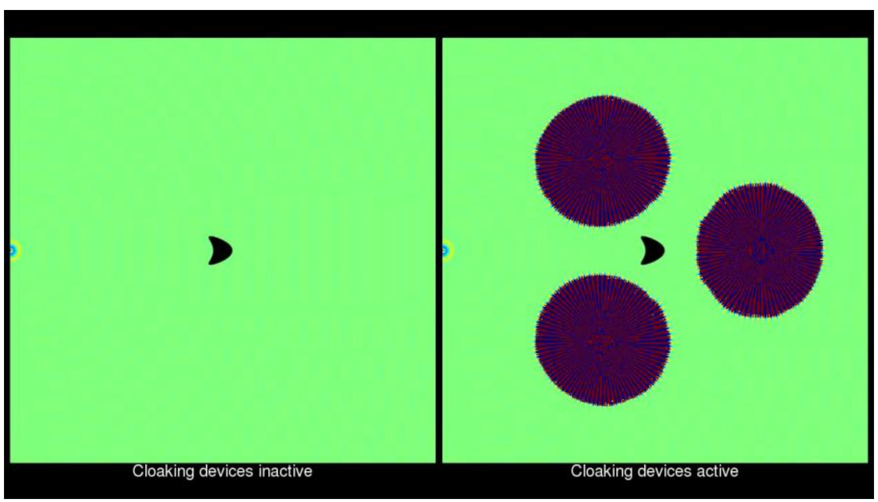
Ando, Ji, Kang, Kim, and Yu, 2015
Li and Liu, 2016

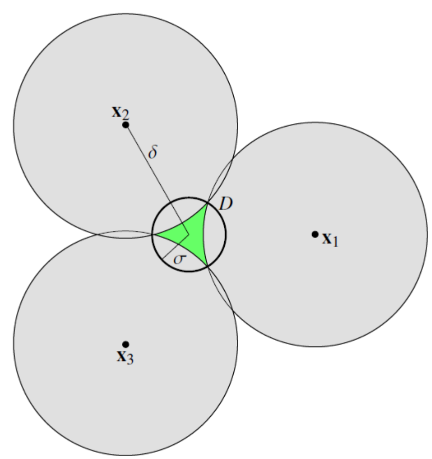
In 2009 I realized that the cloaking due to anomalous resonance was caused by **polarization charges** and therefore one should be able to get a similar, if not better, effect using active sources. A wonderful collaboration with Fernando Guevara Vasquez and Daniel Onofrei on **active exterior cloaking** ensued:

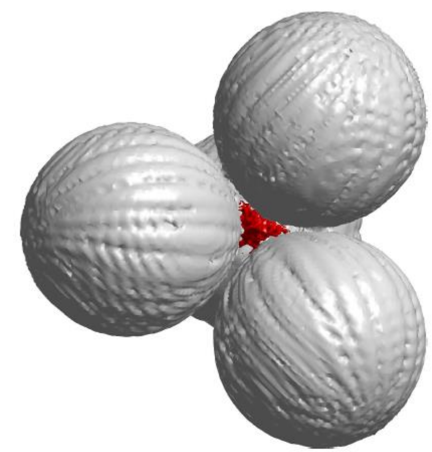


(a) (b)








(b) $|u_d| = 5$

This idea was developed further by others:

Illusions using active sources: Zheng, Xiao, Lai, and Chan(2010)

Active manipulation of fields: Onofrei (2012, 2014),

Sensitivity analysis for active control:

Hubenthal and Onofrei, (2016)

More sources: Norris, Amikulova, and Parnell (2012)

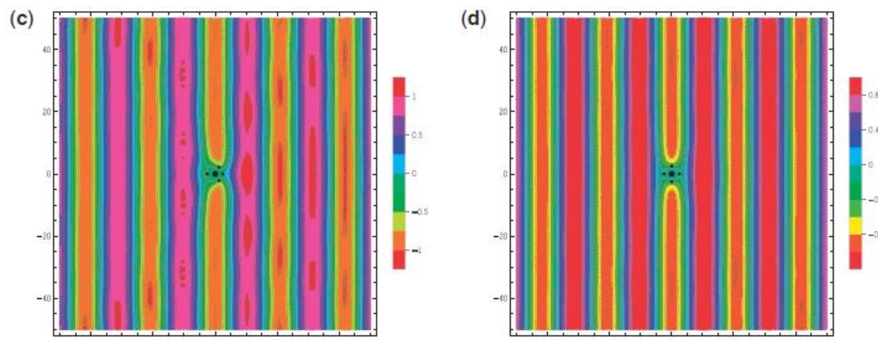
Elastodynamics: Norris, Amirkulova, and Parnell (2012)

In an extremely nice twist of the idea,

O'Neill, Selsil, McPhedran, Movchan, and Movchan (2015)
O'Neill, Selsil, McPhedran, Movchan, Movchan, and Moggach (2016)

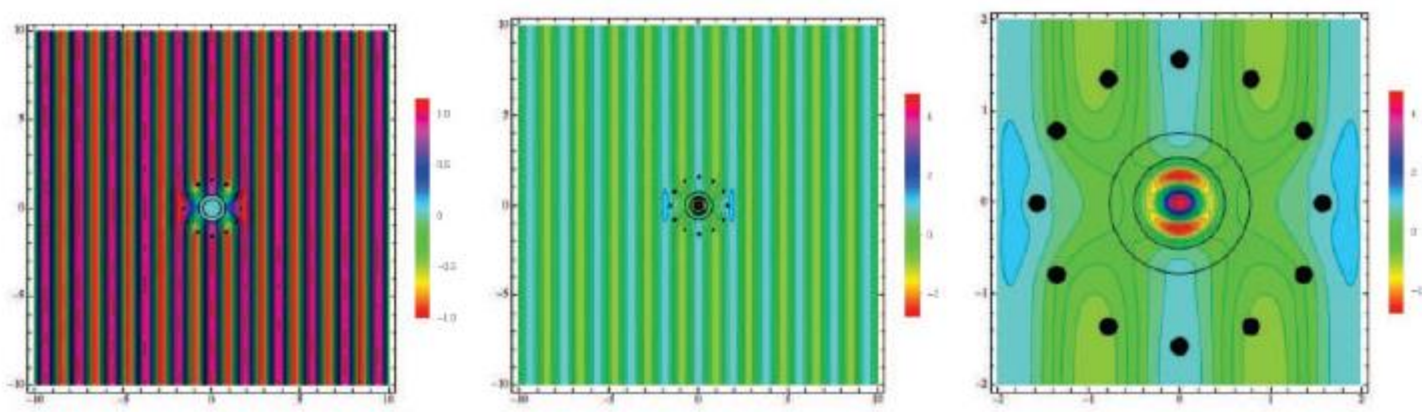
found that for the vibrating plates one could get excellent exterior cloaking **without enormous fields** if one only requires that the cloak **cloaks a given object** and one tailors the cloak to that object.

Non-Resonant Inclusion



One key point: the Green's function is bounded for the plate equation

Resonant Inclusion



(a) (b) (c)

Have others been hurt by Pendry's consistent failure to reference work that preceded his?

Absolutely yes.

Most people think that he was the first to discover "transformation optics" in (2006)
(5500 citations)

But actually it was Dolin (1961)….83 citations (?)

TO THE POSSIBILITY OF COMPARISON OF THREE-DIMENSIONAL ELECTROMAGNETIC SYSTEMS WITH NONUNIFORM ANISOTROPIC FILLING

L. S. Dolin

It was shown that it is possible to investigate three-dimensional systems with nonuniform anisotropic filling by comparison them with other, more simple three-dimensional systems. The examination is made basing on an invariance of Maxwels equations relative to the certain type of transformation of space metric and medium permeability and permittivity.

READ THE ABSTRACT ABOVE . IT IS EXACTLY TRANSFORMATION OPTICS.

$$R(r) \to r. \tag{4}$$

Коэффициенты Ламе этой системы равны $h_R = dr(R)/dR$, $h_\Theta = r(R)$, $h_\varphi = r(R)\sin\Theta$, и для проницаемостей среды получим следующие формулы:

$$\| \varepsilon_{ik} \| = \| \mu_{ik} \| = \begin{vmatrix} \frac{R^2}{r^2(R)} \frac{dr(R)}{dR} & 0 & 0 \\ 0 & \frac{1}{dr(R)/dR} & 0 \\ 0 & 0 & \frac{1}{dr(R)/dR} \end{vmatrix}. \tag{5}$$

Translation Available on my website http://www.math.utah.edu/~milton

Never cited by Pendry, as far as I can see.

Most people **outside mathematics** think he was the first to discover transformation based cloaking in (2006).

But Lassas, Greenleaf and Uhlmann had discovered the key idea back in (2003) for conductivity.

Pendry, Schurig and Smith (2006) **used the same transformation** as Lassas, Greenleaf, and Uhlmann. The cloaking recipe in their paper (now cited 5,550 times) can be seen as a **simple corollary** of combining the ideas of Dolin and Lassas, Greenleaf and Uhlmann.

(Dolin)+(Lassas, Greenleaf, and Uhlmann cloaking)
= (Pendry, Schurig, and Smith cloaking)

What about metamaterials?
Isn't that an area of science which was founded by Sir John Pendry?

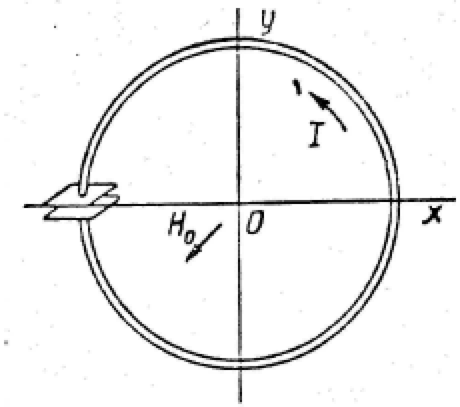
Emphatically no. A good source of information is

S. Tretyakov, Electromagnetic metamaterials: Past, present, and future, *9th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics - Metamaterials 2015,* Oxford, United Kingdom, 7-12 September, 2015 (invited plenary talk). Download slides (7 MB pdf file).

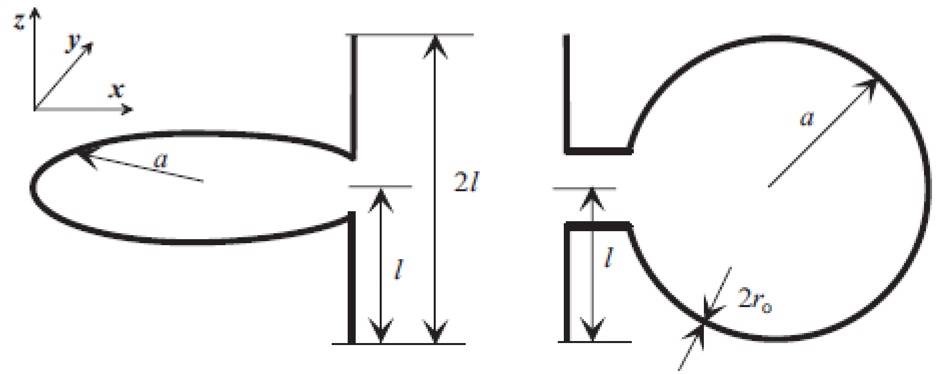
https://users.aalto.fi/~sergei/Tretyakov_slides_Metamaterials2015.pdf

Tretyakov points out that metamaterials have been around since 1898, and now I use some of the information in his slides

Artificial Magnetism Using Split Rings



$$\chi_m^0 = \frac{\omega^2\mu_0^2 C S^2}{1-\omega^2 LC}$$



S.A. Schelkunoff and H.T. Friis, Antennas: Theory and Practice, New York: Wiley, 1952; D. Jaggard, N. Engheta, and many other authors, 1980–2000, S.A. Tretyakov, F. Mariotte, C.R. Simovski, T.G. Kharina, J.-P. Heliot, Analytical antenna model for chiral scatterers: Comparison with numerical and experimental data, IEEE Trans. Antennas Propag., vol. 44, no. 7, 1006-1014, 1996.

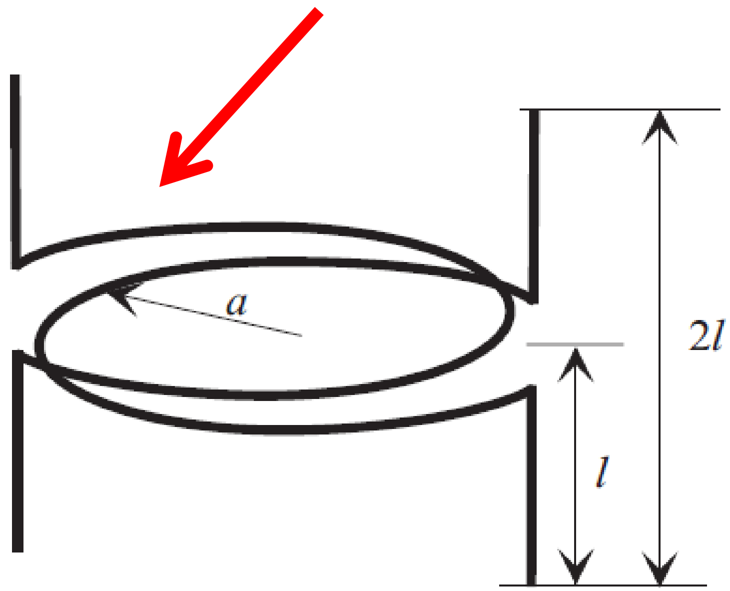
Before

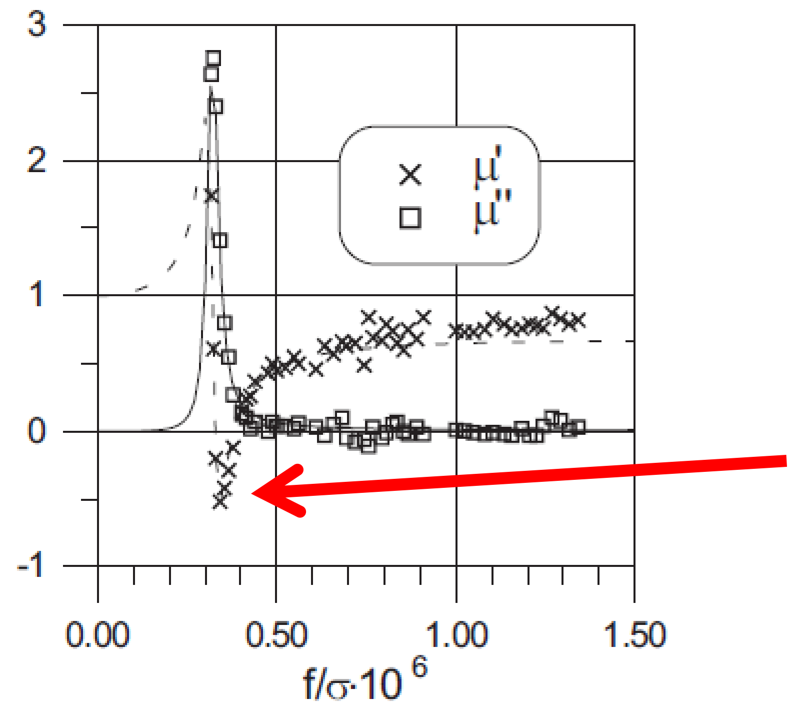
(Partial Tretyakov Slide)

J.B. Pendry, et al., *IEEE Trans. Microwave Theory Techn.*, vol. 47, pp. 2075-2084, 1999

7100 Citations

Arrays of Split Rings giving negative permeability:





A.N. Lagarkov, et al., *Electromagnetics*, vol. 17, no. 3, pp. 213-237, 1997

Before

J.B. Pendry, et al., *IEEE Trans. Microwave Theory Techn.*, vol. 47, pp. 2075-2084, 1999

(Combination of Tretyakov Slides)

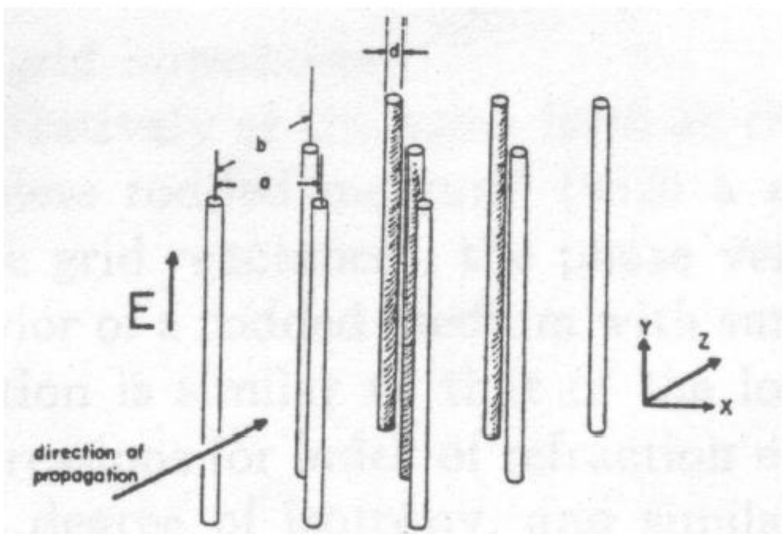
Well, at least wasn't Pendry the first person to discover wire metamaterials?

Pendry et. al. Extremely Low Frequency Plasmons in Metallic Microstructures, (1996)

3700 Citations

No that isn't true.

(Tretyakov Slide)



$$\epsilon_p = \epsilon_0\left(1 - \frac{\omega_p{}^2}{\nu^2+\omega^2} + j\,\frac{\omega_p{}^2\nu/\omega}{\nu^2+\omega^2}\right)$$

J. Brown, Artificial dielectrics having refractive indices less than unity, Proc. IEE, vol. 100, part 4, 51-62, 1953; W. Rotman, Plasma simulations by artificial dielectrics and parallel plate media, IRE Trans. Antennas Propag., 81-96, Jan. 1962.

Artificial dielectrics

(Tretyakov Slide)

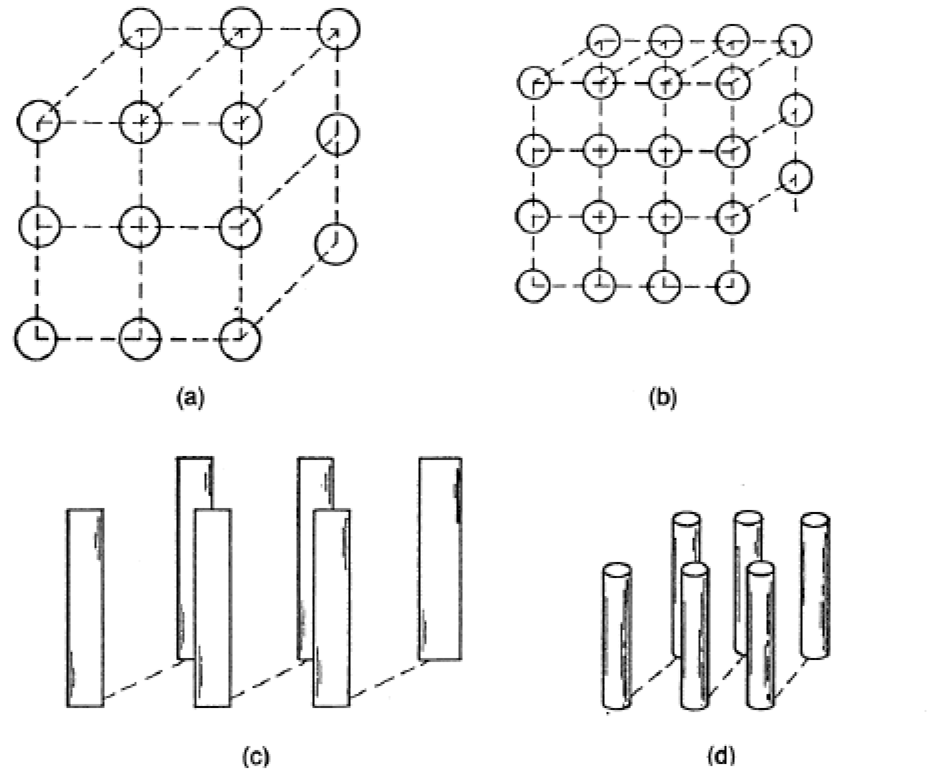


Fig. 12.1. Typical artificial dielectric structures. (a) Three-dimensional sphere medium. (b) Three-dimensional disk medium. (c) Two-dimensional strip medium. (d) Two-dimensional rod medium.

W.E. Kock, Metallic delay lenses, Bell Syst. Tech. J., vol. 27, 58-82, 1948; J. Brown, The design of metallic delay dielectrics, Proc. IRE (London), vol. 97, part III, 45-48, 1950.

This is not a personal vendetta. Professor Pendry has a charming personality, and is clearly a brilliant scientist. He only needs to change his referencing style, particularly when giving talks.

I think we all need to make an effort and not follow the flock, but rather cite papers where the original ideas first appear and not just papers that other people have cited.

Otherwise one can have a snowball effect of injustice.

Also as far as humanly possible to we should try to read those papers we cite, or at the very least try to skim through them: wise advice many years from my brilliant PhD advisor, Michael E. Fisher.

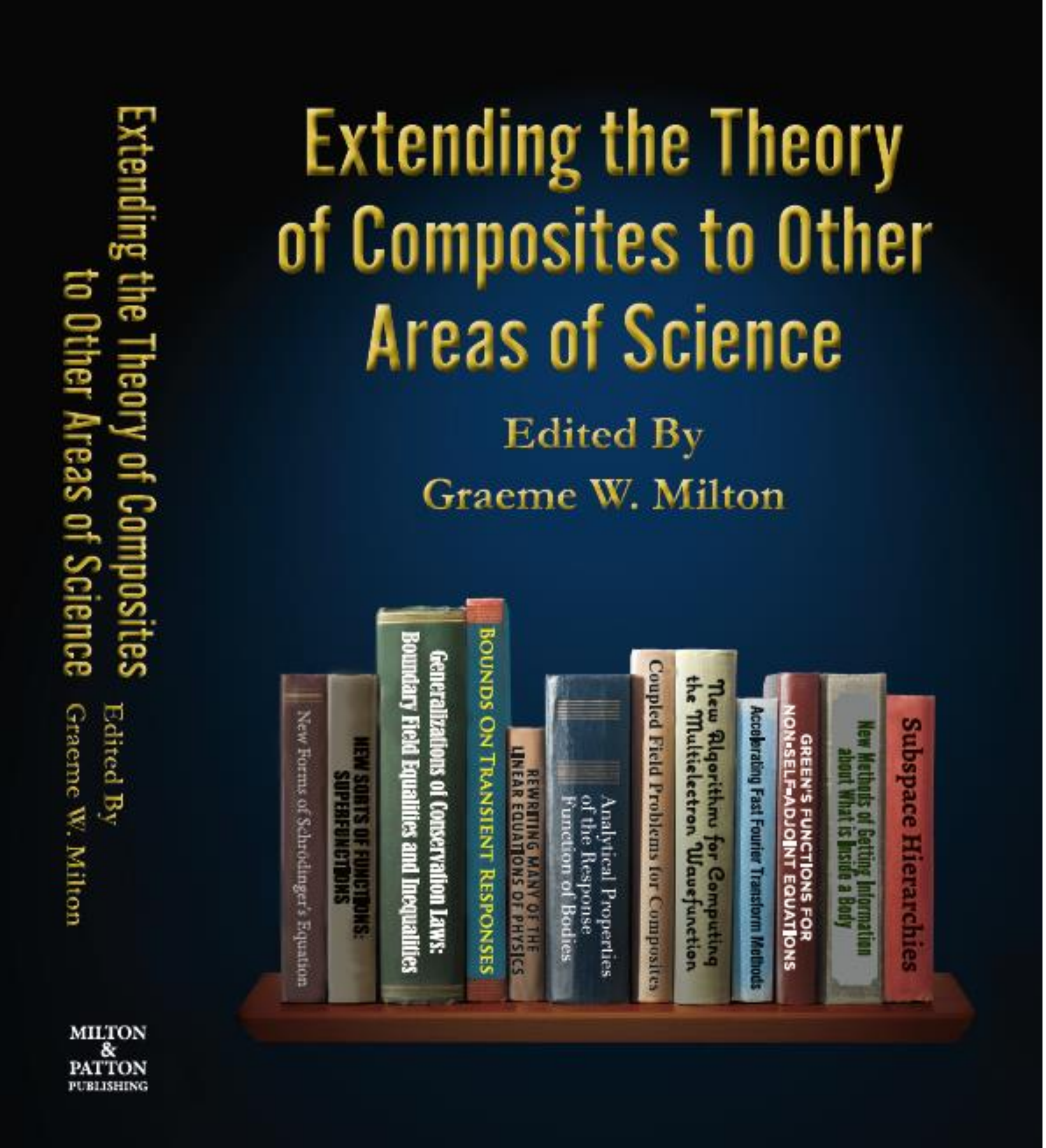
Finally, a very important point due to a close friend (anonymous)*:

Scientific progress will be greatly accelerated if we carefully read what has been done before.

Just think of how much more rapidly the subject of superlensing would have progressed had Sir John Pendry in 2000 read our 1994 paper, cited it, and realized it held the keys to understanding superlensing.

I usually take the route of following the excitement of developing new ideas that come to my mind. But then afterwards I try to see if the path has already been discovered by someone else. This last step is important.

* This slide was inserted after the lecture



Chapters coauthored with:

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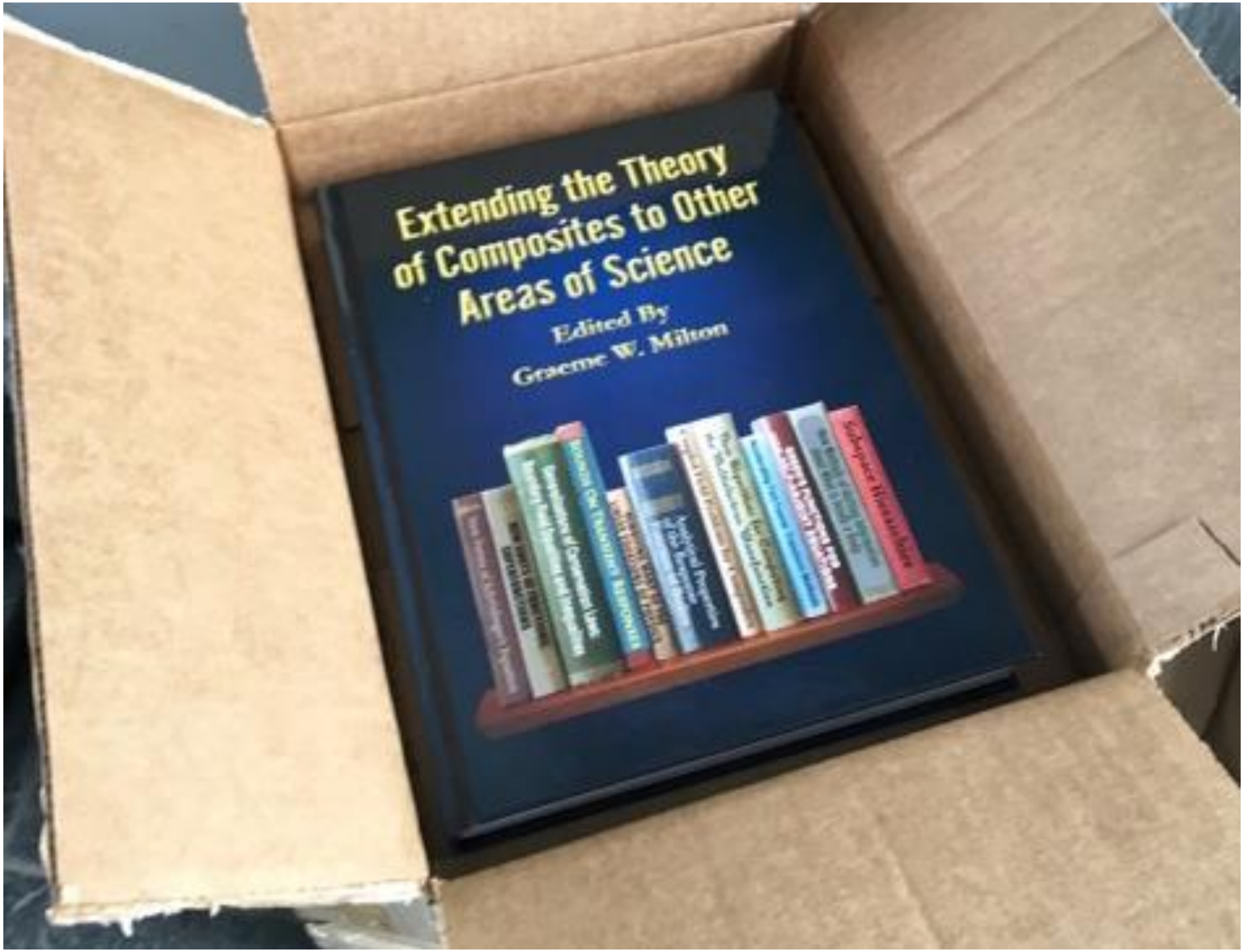

It arrived today. How Exciting!